The World Avoided by the Montreal Protocol

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[1] The impact of increased stratospheric chlorine, averted by controls imposed by the Montreal Protocol, is studied using the UKCA chemistry-climate model. We contrast an atmosphere with 9 ppbv Cl_y, which could have occurred by ~2030, with the present-day loading (3.5 ppbv), and consider the response of climate to resulting ozone perturbations, disregarding the radiative impact of the additional CFCs. Ozone columns decline everywhere, with climate impacts in both polar regions. The additional chlorine leads to a strengthening of the Southern Annular Mode, versus the reference, and Antarctic surface temperature differences resemble observed changes. Over Eurasia, winter surface temperature changes project on the Northern Annular Mode. These high-latitude temperature perturbations (>1 K) are larger than the global mean temperature rises projected over the next few decades, and perhaps comparable with projected regional changes. The Montreal Protocol has not only averted further damage to the ozone layer but has helped prevent significant regional climate change. **Citation:** Morgenstern, O., P. Braesicke, M. M. Hurwitz, F. M. O'Connor, A. C. Bushell, C. E. Johnson, and J. A. Pyle (2008), The World Avoided by the Montreal Protocol, *Geophys. Res. Lett.*, *35*, L16811, doi:10.1029/2008GL034590.

1. Introduction

[2] In the late 1980s, field and laboratory measurements [e.g., *Solomon et al.*, 1986, 1987; *de Zafra et al.*, 1987; *Molina and Molina*, 1987; *Cox and Hayman*, 1988; *Anderson et al.*, 1989; *Kelly et al.*, 1989] allowed the recently discovered Antarctic ozone depletion [*Farman et al.*, 1985] to be attributed to the growth in anthropogenic halogen compounds. The explanation of the ozone loss relied on new insights into chemistry as well as meteorology in the Antarctic lower stratosphere, and the Montreal Protocol, with amendments, was introduced to reverse their upward trends. Missing at the time was the ability to assess the interactions between the ozone changes and climate. An assessment of this link requires climate-chemistry models which have only recently become available [*Austin et al.*, 2003; *World Meteorological Organization (WMO)*, 2003; *Eyring et al.*, 2006].

[3] The impact of ozone depletion on stratospheric temperatures is well established [e.g., *Chipperfield and Pyle*, 1988]; however, its effect on surface climate is less well understood. Some research has focussed on the link between Antarctic ozone loss and surface climate change. For example, the Antarctic Peninsula area has experienced fast warming, while much of the Antarctic interior has cooled [*Vaughan et al.*, 2001]. Models indicate that ozone depletion, via its effect on the Southern Annular Mode (SAM), is implicated in this change [*Thompson and Solomon*, 2002]. There also is evidence for a link between Arctic surface climate change and changes in the Northern Annular Mode (NAM); however, global circulation models driven only with increasing CO_2 do not reproduce these changes [*Moritz et al.*, 2002]. Recent attempts to explain Arctic surface temperature trends did not take into account stratospheric ozone perturbations.

[4] Without the Montreal Protocol, the effective equivalent stratospheric chlorine (EESC, combining the effects of chlorine and bromine) could, depending on the scenario chosen, have reached 9 ppbv by ~2025 [*WMO*, 2007] or even as early as 2002 [*Prather et al.*, 1996] with growth rates typical of the late 1960s and early 1970s. We apply the UK Chemistry and Aerosols (UKCA) climate-chemistry model (section 2) to the problem of how climate would have responded to this increase in chlorine. In two simulations we contrast an atmosphere with a total chlorine (not EESC) loading of 9 ppbv (the "World Avoided") with one with 3.5 ppbv, reached in the late 1990s [*WMO*, 2007]. Otherwise the simulations are identical. We focus on the effects of the avoided ozone depletion on climate; hence the only change in radiative forcing considered arises from the changes in ozone. In the radiation calculations other greenhouse gases are assumed invariant and representative of the year 2000. In the near future we are committed to a greenhouse-gas driven increase in global mean temperature of about 0.2 K/decade [*Intergovernmental Panel on Climate Change (IPCC)*, 2007], while a three-fold increase in CFCs might give an additional radiative forcing of about 0.6 W/m^2, which might also contribute, approximately, a few tenths of a degree rise to global mean temperatures. *Velders et al.* [2007] have discussed in detail the direct impact on radiative forcing of the CFC emissions avoided by the Montreal Protocol.

2. The Model

[5] The UKCA model is based on the Met Office Unified Model (MetUM). We use an atmosphere-only version similar to the Hadley Centre Global Environment Model version 2. *Cullen et al.* [1997] describe its dynamical core. The model is run at a resolution of 3.75° × 2.5° with 60 hybrid-height levels in the vertical, extending to 84 km.

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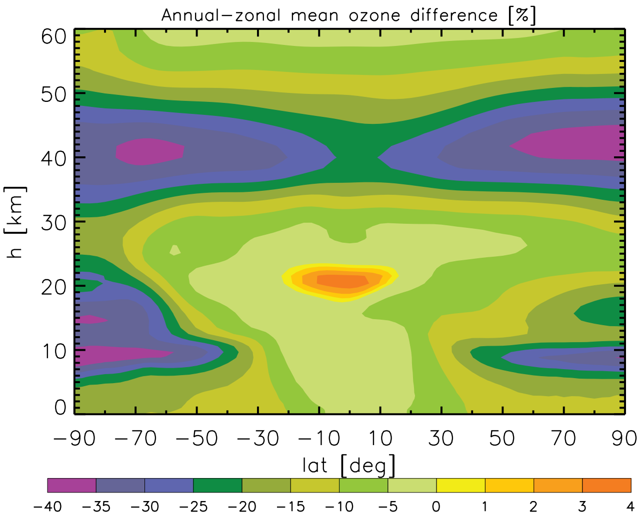

Figure 1. Zonal- and multiannual-mean ozone difference in percent relative to the 3.5 ppbv Cl_y simulation, between the 9 ppbv and the 3.5 ppbv simulations.

There is a representation of non-orographic gravity waves [*Scaife et al.*, 2002]. Radiation follows *Edwards and Slingo* [1996] with 9 bands for long- and 6 for shortwave radiation. We prescribe AMIP2 sea surface temperatures (SSTs) and sea ice (http://www-pcmdi.llnl.gov/projects/amip/AMIP2EXPDSN/BCS/bcsintro.php) for the period September 1989 to August 1999. Ocean feedback is important to climate, especially on long timescales. We focus here on relatively short periods (~3 decades) where the limitation of using prescribed SSTs is less serious.

[6] We have added to the MetUM a stratospheric chemistry scheme similar to *Chipperfield and Pyle* [1998] with kinetic data based on recent recommendations [*Atkinson et al.*, 2004, 2007; *Sander et al.*, 2003]. We use a non-families solver (derived from *Wild and Prather* [2000]) and prescribe sulphate aerosol surface area densities [*Thomason et al.*, 1997]. There is a strong volcanic signature due to the Mt Pinatubo eruption in this dataset. The direct radiative impact of this volcanic aerosol is however not represented in the model. Both simulations assume a contemporary bromine loading of 20 pptv [*WMO*, 2007]. For chemistry, long-lived tracers and halogen source gases are given uniform and time-invariant lower boundary conditions representative for the 1990s, except for the CFCs, which are increased in the 9 ppbv simulation. For radiation, time- and spatially invariant fields (identical in the two simulations) are assumed for all greenhouse gases except O_3 and H_2O, with numbers representative of the 1990s.

[7] The present-day run compares well with observations and falls within the range of model performances discussed by *Eyring et al.* [2006]. Note that like other models, the present-day run does not achieve complete ozone depletion in the springtime Antarctic lower stratosphere, in the zonal and monthly mean.

3. Impacts on Ozone

[8] Increasing stratospheric chlorine to 9 ppbv profoundly impacts modeled ozone. Column ozone decreases everywhere, with losses ranging from 5% in the tropics, through mid-latitude losses of 10–15%, to ~30% in Arctic and ~60% in Antarctic spring, i.e., a drop in the zonal and monthly mean from around 180 to about 70 Dobson Units (not shown). The integrated loss between 60°S and 60°N is 8.3%. These losses are larger than recent observed ozone changes, where the observed mid-latitude ozone decline between 1980 and 1999–2001 is 3% in the Northern Hemisphere and 6% in the Southern Hemisphere; integrated 60°S–60°N ozone for 2002–2005 is ~3.5% lower than the mean 1964–1980 values [*WMO*, 2007]. Note that in the recent record there is no discernible trend in observed tropical ozone columns [*WMO*, 2007], but at 9 ppbv of Cl_y there would have been a significant loss of tropical ozone. Our calculations show that the Montreal Protocol has prevented further, substantial ozone losses which would have led to increased surface UV radiation with consequences for human health [*WMO*, 2007].

[9] Large modeled ozone loss (~40%) results in the upper stratosphere (Figure 1). Here large ozone loss had been predicted prior to the discovery of the ozone hole [*Molina and Rowland*, 1974; see also *Pyle*, 1980]. Losses are also predicted for both polar vortices. In the Antarctic, between 14 and 21 km, the loss between the 3.5 ppbv and 9 ppbv runs reaches 80% in spring. In the Arctic lower stratosphere, additional loss of about 40% occurs in March when stratospheric chlorine rises from 3.5 to 9 ppbv. The high-latitude changes around the tropopause are small in absolute terms. In the tropics (and in the summer hemisphere, not shown in Figure 1) around 21 km we find a small increase of ozone. This is consistent with "self-healing", when depletion aloft allows more UV penetration and thus increased ozone production at lower altitudes. There is also a decrease of extratropical tropospheric ozone of 5 to 15% which is related, through stratosphere-troposphere exchange, to the midlatitude lower-stratospheric losses.

4. Impacts on Climate

[10] The upper stratosphere cools by more than 6 K (Figure 2), inducing a change in lapse rate. The high-latitude lower stratosphere at 10 to 20 km cools by 2–3 K. Between 25 and 40 km both vortices warm; the ozone reduction lower down allows increased upwelling of 9.6 μm radiation which heats this region [*Chipperfield and Pyle*, 1988]. Mean age of air [*Pollock et al.*, 1992] at 30 km decreases by 0.2 to 0.4 years. Both polar vortices strengthen, but the anticorrelation between the strength of the polar jet and the polar ozone column found in the Arctic [*Braesicke and Pyle*, 2003] no longer holds at 9 ppbv of chlorine. A threshold has been passed such that the Arctic ozone column experiences a transition from dynamical control to chemical domination in the high-chlorine case.

[11] The large ozone loss leads to surface warming over both poles of nearly 1 K in the annual and zonal mean. In the tropics and over much of the oceans, the surface changes are generally small (recall that SSTs are the same in both experiments; section 2). There is an impact on temperature over Antarctica in spring, e.g., a 2 K warming in the lee of the Antarctic Peninsula (Figure 3) which exceeds the standard deviation of monthly-mean temperature, and cool-

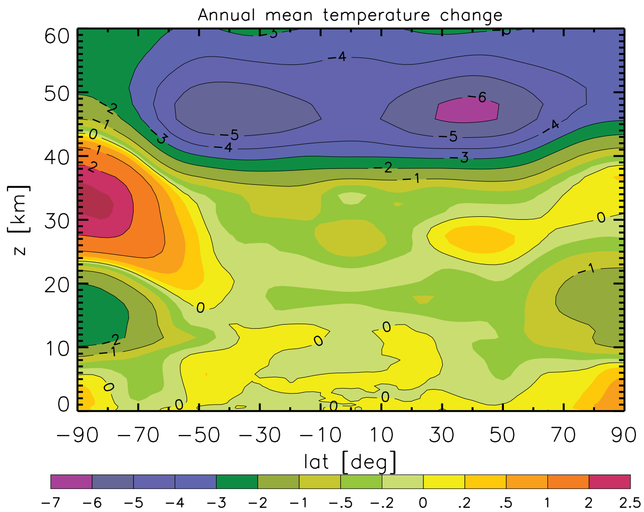

Figure 2. Zonal- and multiannual-mean difference in temperature, in K, between the 9 ppbv and the 3.5 ppbv simulations.

ing over parts of the continent. There are also large temperature changes in Northern winter, with continental warming and cooling over the Eastern Arctic Ocean (Figure 4). This constitutes an example of stratosphere-troposphere coupling. The Antarctic surface temperature signal is similar to observed recent change as shown by *Thompson and Solomon* [2002] and modeled by *Gillett and Thompson* [2003] and *WMO* [2007]. Note however the difference in seasons between their results and ours. Stratospheric ozone depletion leads to a strengthening of the polar jet, a feature of the SAM [*Thompson et al.*, 2000], coupling to increased tropospheric circumpolar winds. Around the Antarctic Peninsula, this increases lee cyclogenesis [*Lubin et al.*, 2008]. Although our model does not properly resolve these eddies, the associated increased poleward heat transport is represented.

[12] The Arctic winter surface temperature signal is large compared to historic climate change [see, e.g., *IPCC*, 2007], indicating that the avoided ozone loss would have had a substantial climate impact. In many places the signal exceeds in absolute terms the standard deviation of seasonal-mean temperature of the reference simulation. Figure 4 reveals a temperature anomaly during NH winter, descending from 40km in November to the upper troposphere in February. *Baldwin and Dunkerton* [2001] discuss "stratospheric harbingers", i.e., stratospheric precursors of tropospheric weather anomalies apparent in meteorological analyses. In a high-chlorine world the coupling between the troposphere and the stratosphere becomes stronger. January temperature anomalies above 15 km in the stratosphere are annular, but this simple pattern does not progress towards the surface. DJF surface temperature anomalies indicate cooling of up to 2 K over parts of Western Europe and Siberia, and warming over the Arctic Ocean, Greenland and North America. The surface temperature and pressure anomalies project on the NAM [*Ostermeier and Wallace*, 2003] over Eurasia. Over North America, there is a larger areal extent of the continental warming modeled here. Note that models that include increasing CO_2, but exclude stratospheric ozone chemistry, produce a more zonal pattern of warming in the Northern Hemisphere than seen here, maximizing over the North Pole, but fail to account for much of the geographical detail of global warming evident from the observational record, for example an asymmetry in warming between the North American Arctic and Siberia [*Moritz et al.*, 2002; *IPCC*, 2007]. While our simulations are not equivalent to those discussed by *Moritz et al.* [2002], it is evident that coupled stratospheric ozone chemistry leads to additional detail appearing in the geographical signature of surface temperature change which bears some similarity to the observed changes, e.g., a relatively strong cooling over the North Atlantic and more pronounced warming over northern North America than over Siberia.

[13] We calculate a net radiative forcing due to ozone and temperature changes of $-0.05 \mathrm{W/m^2}$. This is almost the same as that caused by the changes in stratospheric ozone during the 20th century [*IPCC*, 2007]. It excludes the competing positive radiative forcing due to the increased halocarbons and CO_2 [*Forster and Joshi*, 2005; *Velders et al.*, 2007; *IPCC*, 2007]. These global forcings could be large: perhaps +0.5 $\mathrm{W/m^2}$ due to CO_2 increases by 2020–2030, assuming scenario A1b [*IPCC*, 2007], and a similar forcing from the increase in the CFCs [*Velders et al.*, 2007]. We would nevertheless expect the impact of the ozone change to be less spatially homogeneous and to maximise in high latitudes. Indeed the pattern of calculated polar temperature change shown in Figures 3 and 4 shows largest temperature changes, up to more than 2 K, there. This is certainly comparable to projected changes due to greenhouse gases [see, e.g., *IPCC*, 2007, Figure SPM.6] for the same period.

5. Summary

[14] Without the Montreal Protocol, a continued build-up of stratospheric halogens would have led within a few

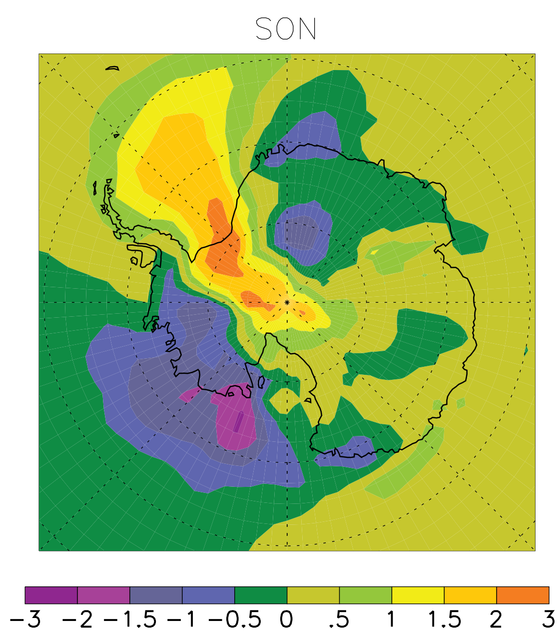

Figure 3. Difference in surface temperature between the high-chlorine and reference simulations in Southern spring, in K.

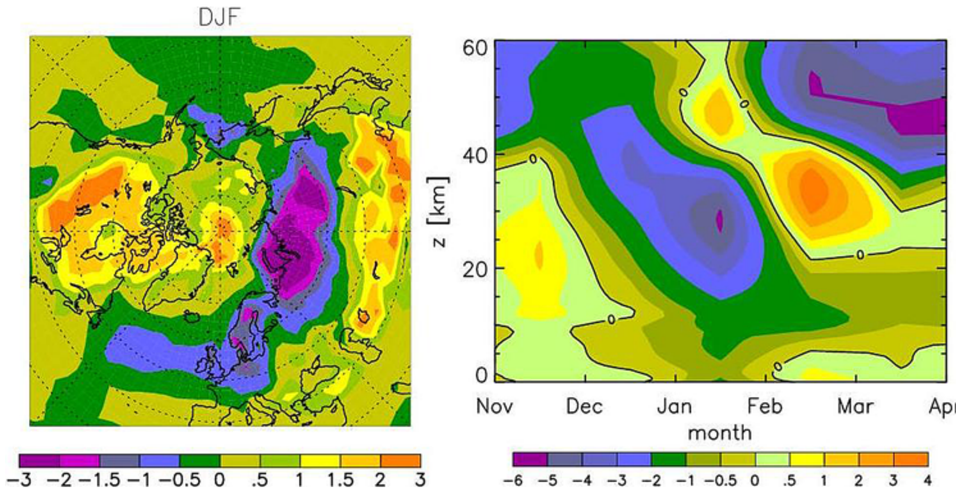

Figure 4. (left) Same as Figure 3 but for the Arctic, in Northern winter. Note the different scales. (right) Zonal- and 10-year mean temperature difference, averaged between 60 and 70°N, in K.

decades to much larger ozone depletion than experienced hitherto. This would have had a large direct impact on stratospheric temperatures and a strengthening of the Brewer-Dobson circulation, with mean age of air at 30 km decreasing by 0.2 to 0.4 years. The high-latitude ozone depletion would also have had a large effect on surface climate, with a further enhancement of the warming in the lee of the Antarctic Peninsula, similar to the observed surface temperature change, and a strengthening of the SAM. In the Arctic, the avoided ozone loss is associated with a warming of the Arctic Ocean and North America, with cooling over Western Europe and Siberia. These predicted changes are comparable to those expected by 2025 due to greenhouse gases [*IPCC*, 2007]. Changes from different forcings are not expected to necessarily add linearly; further calculations are needed to assess the overall impact of changes in CFCs and other greenhouse gases including CO_2 and the change in ozone. Nonetheless, we conclude that the Montreal Protocol has provided an enormous benefit not only to the stability of the stratospheric ozone layer but also to surface climate.

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